Buoyant Outflows in the Presence of Complex Topography

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LONG-TERM GOALS

The overall goals are closely linked to several ancillary projects. The long term scientific goals are to (a) understand the physical mechanisms that control the exchange between two marginal seas with substantially different water mass characteristics (Aegean Sea and Black Sea) through a complex system of straits (Turkish Straits System); (b) quantify the pathways of the buoyant outflow and evaluate the influence on the dynamics of the receiving coastal areas, as well as on the Mediterranean Sea at large. The long term operational goal is to develop a high resolution numerical model of the Northern Aegean Sea, nested within a coarser Mediterranean Sea model and coupled to a high resolution, unstructured grid model of the Turkish Straits system, which in itself will be coupled to a Black Sea model.

OBJECTIVES

The main *scientific objectives* are to:

a) provide new insights in the understanding of plume dynamics, analyzing the development of a plume that is generated by a buoyant outflow through a narrow strait and its evolution through a topographically complex marginal sea;

b) examine the relative role of buoyancy, wind stress and topography in determining the seasonal and inter-annual variability in the development and evolution of the Dardanelles plume;

c) quantify the transport rates and pathways of the low-salinity waters of Black Sea origin that enter the Aegean Sea (and hence the Mediterranean) through the Dardanelles Strait;

d) study the influence of the flow exchange through the Dardanelles Strait on the Aegean Sea coastal flows, cross-shelf exchanges and basin-wide eddy field;

e) examine if the inter-annual variability of the Dardanelles plume (in the context of changing outflow properties and regional atmospheric forcing) is related to changes in the export of dense waters from the Northern Aegean to the Eastern Mediterranean Sea.

The main *operational objectives* are to:

f) explore a novel approach in ocean modeling, by developing techniques to parameterize flow exchange through narrow straits that cannot be properly resolved in ocean models;

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14. ABSTRACT
The overall goals are closely linked to several ancillary projects. The long term scientific goals are to (a) understand the physical mechanisms that control the exchange between two marginal seas with substantially different water mass characteristics (Aegean Sea and Black Sea) through a complex system of straits (Turkish Straits System); (b) quantify the pathways of the buoyant outflow and evaluate the influence on the dynamics of the receiving coastal areas, as well as on the Mediterranean Sea at large. The long term operational goal is to develop a high resolution numerical model of the Northern Aegean Sea, nested within a coarser Mediterranean Sea model and coupled to a high resolution, unstructured grid model of the Turkish Straits system, which in itself will be coupled to a Black Sea model.

15. SUBJECT TERMS

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g) enhance the predictive capability of operational Navy models, by developing and testing a methodology to link the Mediterranean and Black Sea basins that are currently uncoupled in all available global and regional Ocean General Circulation Models;

h) help optimize Navy missions in strategic areas of complex topography;

i) contribute to a prediction tool that is essential for optimizing Navy missions, especially near watersheds and strategic straits.

APPROACH

A high resolution (1/50 degree, ~1.8 km) numerical model has been applied on the Northern Aegean Sea (NAS). The nested model is based on the Hybrid Coordinate Ocean Model (HYCOM; http://hycom.rsmas.miami.edu), to take advantage of the flexible isopycnal-sigma-zlevel coordinate system and advanced mixing schemes, both important factors for the successful simulation of plume dynamics in areas of strong shallow to deep topography transitions, as in the study domain. Boundary conditions have been provided through collaboration with NRL-SSC (A. Wallcraft and B. Kara); a regional Mediterranean Sea HYCOM model (resolution 1/25 degree) has been developed and has been running operationally since 2003 with the Navy Coupled Ocean Data Assimilation (NCODA; Cummings, 2005. For the purposes of this study, a non-assimilative MED-HYCOM simulation has also been executed. Atmospheric forcing Navy products are available to us from NRL: NOGAPS (1 and 1/2 degree) and COAMPS (up to 1/5 degree). Higher resolution products (currently 1/10 degree, evolving to 1/20 degree) are available through collaboration with the Hellenic Center for Marine Research (POSEIDON atmospheric model, http://www.poseidon.hcmr.gr, which is based on SKIRON/ETA forcing, http://forecast.uoa.gr/, but with assimilation of real-time data and on-line coupling of coarse and fine domains, see Papadopoulos et al., 2002). Different parameterizations of the Dardanelles outflow will be examined: (i) as a river (near surface discharge); (ii) as a two-layer system of inflow-outflow with transport and mass characteristics prescribed from historical and new data (collaboration with Ewa Jarosz and Bill Teague, NRL-SSC); (iii) through coupling to a straits model (collaboration with Cheryl-Ann Blain, NRL-SSC).

Two types of simulations will take place: process oriented (idealized and/or climatological forcing) and realistic (high frequency forcing). The process oriented simulations will focus on the dynamics of the buoyant discharge and the interaction between the strait and the main topographic features near the discharge site that modify the initial plume evolution. The role of wind stress will be evaluated for periods of persistent northerlies / southerlies which are upwelling / downwelling favorable for the eastern Aegean, respectively. These simulations will elucidate the relative importance of the major circulation forcing mechanisms that govern plume development. The simulations with high frequency atmospheric forcing will cover periods when data are available for model evaluation. Specific circulation features known from Aegean observational studies (especially eddies and fronts) will be employed to quantify the effects of improved boundary conditions at Dardanelles. Data sources are reviewed in Olson et al. (2007). Trajectories of synthetic floats released at various locations within and outside the Dardanelles buoyant plume will be computed. Available drifter data (Olson et al., 2007) will be used to compare observed and synthetic float pathways. The data evaluated performance of the NAS-HYCOM model will guide the Dardanelles parameterization choice and will be an important step toward the optimal coupling of the Aegean and Black Seas through the TSS.

WORK COMPLETED

The study started on June 2008. The work so far has concentrated on technical aspects of model set-up, nesting and forcing. The NAS-HYCOM model is up and running. The model domain extends from 22.5^{o}E to 27^{o}E and from 39^{o}N to 41^{o}N. The grid resolution is 1/50^o and contains 233x173 cells; 20 hybrid layers are employed in the vertical. The bathymetry is derived from the NOAA General Bathymetric Charts of the Oceans (GEBCO) 1 min bathymetry (http://www.ngdc.noaa.gov/mgg/gebco/grid/1mingrid.html). In addition, extensive corrections for island passages and straits have been added, merging with local bathymetric data sets. Minimum depth is 2.4m and the deep areas reach 1500m. The Dardanelles Strait is currently treated as a "river". We have employed recent advances in the mapping of the vertical coordinate (developed at UM in collaboration with NRL), similar to Kourafalou et al. (2008); this is important for coastal applications, especially in topographically and dynamically complex coastal environments, as in the NAS case.

Process oriented simulations have already taken place with and without: wind forcing, Dardanelles outflow and river inputs. Realistic simulations are under way for the 2002-2003 period. Twin experiments with two atmospheric data sets have been carried out: NOGAPS (1/2^o resolution) and POSEIDON/SKIRON (1/10^o resolution). The latter has allowed a model inter-comparison with a simulation of the NAS-POM model (based on the Princeton Ocean Model, Kourafalou and Tsiaras, 2007). The nesting of the NAS-HYCOM to the MED-HYCOM has proven much more effective than nested simulations with the NAS-POM model, where a long initialization procedure was necessary in order to retain the general circulation characteristics of the Northern Aegean Sea.

RESULTS

The outflow of waters of Black Sea origin (BSW) in the Aegean Sea through the Dardanelles Strait appears to have a significant impact on the basin-wide circulation, with implications on the Aegean water mass characteristics and the formation of eddies and fronts. This is an important finding that has been overlooked in all existing Mediterranean models (including the MED-HYCOM) that usually have a closed boundary (no BSW outflow) at the Dardanelles Strait. Results so far have focused on seasonal variability. An example is given in Fig. 1, showing near surface salinity fields for early April and late May. The latter is associated with the onset of seasonal stratification, which facilitates the offshore spreading of plume waters (see cross-section of temperature and salinity from the Dardanelles outflow to the western Aegean in Fig. 2). This example illustrates the transition from "typical" winter-spring conditions (low salinity areas are concentrated in the Dardanelles dominated Northeastern Aegean and in the river dominated Northwestern Aegean) to "typical" summer-fall conditions (substantial freshening in the entire Northern Aegean with tendency for intrusions of BSW waters in sub-basins and influence on coastal areas at great distances from the Dardanelles Strait). The results agree with data findings in Kontoyiannis et al., (2003) and simulations with climatological forcing in Kourafalou and Barbopoulos (2003); Kourafalou et al. (2003).

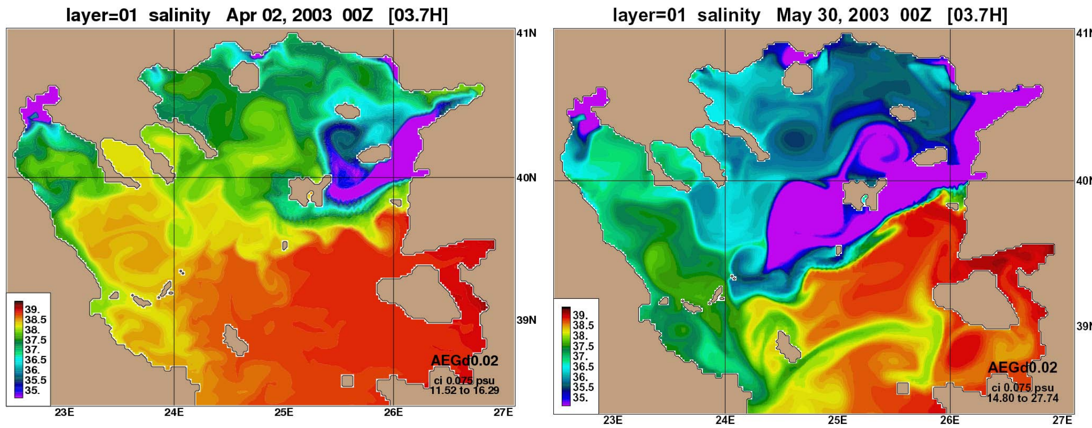

Figure 1: Horizontal surface salinity distribution for April 2, 2003 (left) and May 30, 2003 (right).

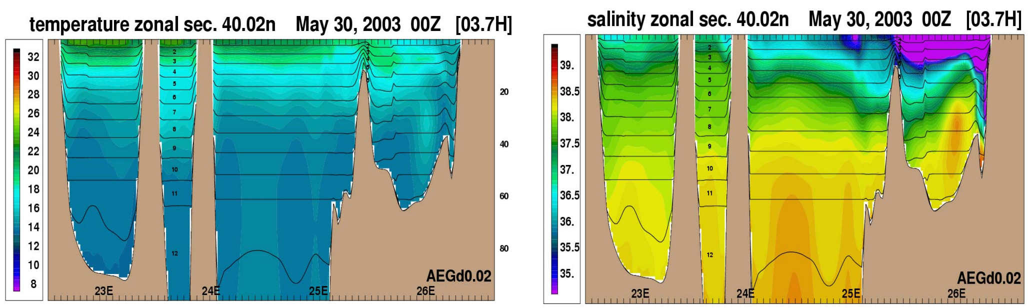

Figure 2: Temperature (upper) and salinity (lower) across the NAS-HYCOM model domain at 40°N corresponding to the 5/30/03 near surface salinity distribution in Fig. 1.

The simulations confirm that the complex topography of the Northern Aegean Sea requires particular attention to the adequate resolution of passages and straits (Kourafalou and Tsiaras, 2007). Preliminary tests with varying topography of the Dardanelles Strait and the passages between islands near the outflow have shown that the pathways of waters of Black Sea origin through the Aegean Sea can be substantially altered. The resolution of the wind fields also appears to have an impact on the BSW pathways. An example is given in Fig. 3, where the near surface velocity fields and the initial (near field) BSW pathways have been computed for the twin experiments with NOGAPS and POSEIDON/SKIRON forcing fields, respectively. Prevailing southward winds appear in both wind fields, leading the BSW flow mainly south of the Limnos island (located at ~25.3 °N, 39.8 °W). However, the higher spatial variability of the POSEIDON atmospheric model allows a divergence in the wind field in the vicinity of the outflow, which creates a bifurcation in the BSW pathway, adding a component north of Limnos. The significance of such changes is that the former favors a direct westward pathway and subsequent exit of BSW toward the South Aegean along a western coastal current (Olson et al., 2007; Kourafalou and Tsiaras, 2007), while the latter allows freshening of the Northern Aegean shelf areas with both local effects (implications on coastal ecosystem changes) and “global” effects (influence on the pre-conditioning of the N. Aegean for dense water formation and its export to the Eastern Mediterranean, Zervakis et al., 2000).

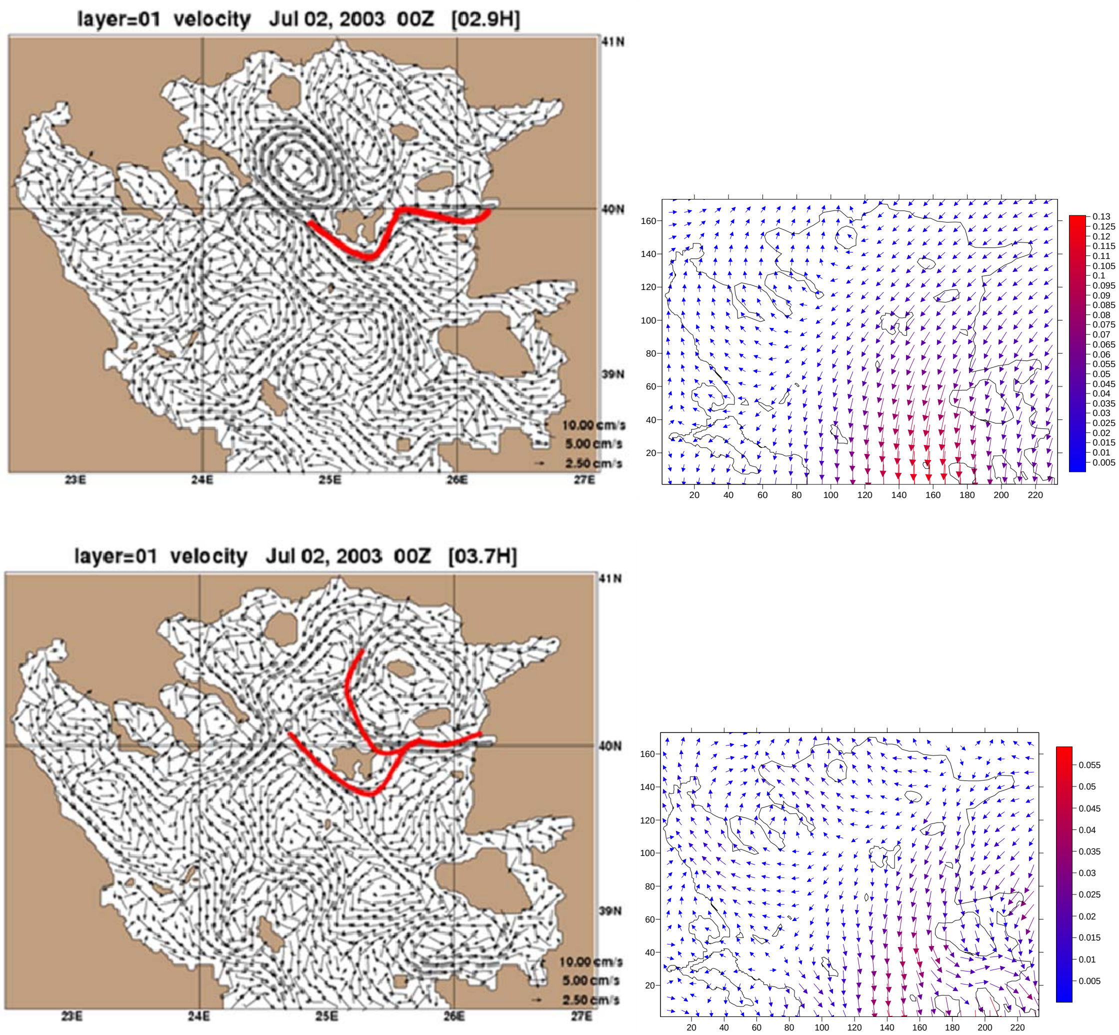

Figure 3: Near surface velocity (left) and winds (right) for July 2, 2003 and from the twin experiments with NOGAPS (upper) and POSEIDON/SKIRON (lower) forcing. The thick red line marks the predominant pathways of waters of Black Sea origin, introduced through the Dardanelles outflow.

IMPACT/APPLICATIONS

This study will set the basis for evaluating improvements in the predictability skill of Aegean Sea and Mediterranean Sea models, by developing and evaluating, for the first time, a data based parameterization of the outflow of waters of Black Sea origin through the Dardanelles Strait. Analysis of numerical simulations and process oriented experiments on the resulting buoyant plume will advance the knowledge on the dynamics that control (a) the exchange of two basins through straits and (b) the transport rates and pathways of the buoyant waters under the influence of high frequency / high resolution atmospheric forcing and in the presence of complex topography. This study will also provide the Aegean Sea model component of a fully coupled Aegean Sea - Turkish Strait System - Black Sea modeling system, which will serve as a Navy prototype for similar areas of marginal seas connected by straits. In addition, the future coupling of the high resolution North Aegean HYCOM model with an unstructured grid model of the TSS and the use of data to evaluate the coupled system will be a valuable benchmark for the modeling of coupled coastal and wetlands models that are critical for optimizing Navy missions. The seasonal and inter-annual variability of the plume controlled salinity distributions will also serve as the basis for the study of biophysical implications, related to the contribution of the eutrophic Black Sea waters on water clarity and productivity of the Northern Aegean Sea.

RELATED PROJECTS

This study is the ONR funded component of an international effort; the extensive collaboration allows considerable leveraging and data sharing.The University of Miami (UM/RSMAS), the Naval Research Lab (SSC and MRY) and the NATO Undersea Research Center (NURC) have been working closely together to establish the scientific objectives and the collaboration logistics to improve the understanding of inter-basin exchanges through straits. The study area chosen for the development of a comprehensive project that will serve as a baseline for the related scientific objectives is the Turkish Straits System (TSS) and the outflows (Northern Aegean Sea and Western Black Sea). The NURC R/V Alliance completed the first data campaign in August-September 2008 (head of the NURC/TSS08 mission: S. Besiktepe). NRL-SSC (PIs E. Jarosz and B. Teague) deployed moored instruments in the TSS (including in the Dardanelles Strait). In addition, we collaborated in the planning of CTD casts and drifter releases within the Dardanelles plume. A total of twelve drifters were released in sets of three instruments at four different locations. The drifters were provided by NURC and by an ancillary ONRG-NICOP funded project for a TSS drifter study (PI P.M. Poulain). A unique data set is expected, which will be availbale to us and provide updated estimates of the Dardanelles outflow. In addition, an ancillary project at NRL-SSC (PI C.A. Blain) will utilize these measurements to calibrate a high resolution, unstructured grid model of the TSS, currently under development. The North Aegean model developed in this project will be eventually coupled with the TSS model.

An ancillary European project has been funded by the EU (Integrated Project SESAME: http://www.sesame-ip.eu/); the lead Institute is the Hellenic Center for Marine Research (HCMR). The PI of the project reported herein is an external collaborator of HCMR; leveraged EU funds include Ph.D. student and post-doc support. In addition, data available to us at no cost to ONR include new hydrographic data in the vicinity of the Dardanelles outflow and re-analysis of SeaWiFS imagery for the entire Aegean Sea.

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